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High strength sewage treatment in a UASB reactor and an integrated UASB-digester system

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Abstract

The treatment of high strength sewage was investigated in a one-stage upflow anaerobic sludge blanket (UASB) reactor and a UASB-digester system. The one-stage UASB reactor was operated in Palestine at a hydraulic retention time (HRT) of 10 h and at ambient air temperature for a period of more than a year in order to asses the system response to the Mediterranean climatic seasonal temperature fluctuation. Afterwards, the one-stage UASB reactor was modified to a UASB-digester system by incorporating a digester operated at 35 °C. The achieved removal efficiencies in the one-stage UASB reactor for total, suspended, colloidal, dissolved and VFA COD were 54, 71, 34, 23%, and −7%, respectively during the first warm six months of the year, and achieved only 32% removal efficiency for COD total over the following cold six months of the year. The modification of the one-stage UASB reactor to a UASB-digester system had remarkably improved the UASB reactor performance as the UASB-digester achieved removal efficiencies for total, suspended, colloidal, dissolved and VFA COD of 72, 74, 74, 62 and 70%. Therefore, the anaerobic treatment of high strength sewage during the hot period in Palestine in a UASB-digester system is very promising.

Keywords: Anaerobic treatment; Sewage; Suspended solids; UASB-digester; UASB

1. Introduction

The upflow anaerobic sludge blanket (UASB) reactor is widely used for sewage treatment in tropical countries, such as India and Brazil. In those countries, the ambient temperature ranges between 20 and 30 °C throughout the year (Von Sperling and Chernicharo, 2005; Aiyuk et al., 2006) and sewage is of low to medium strength. The current challenge in anaerobic technology development is to amend the system to treat municipal sewage in extreme situation. For instance, in Palestine and Jordan sewage is characterised with high COD concentrations of more than 1000 mg/L with high fraction of suspended COD (COD_{ss}) (up to 70%) and fluctuating temperature between winter and summer in the range 15–25 °C (Mahmoud et al., 2003a; Halalsheh et al., 2005). Previous research had demonstrated that the performance of one-stage UASB reactors at low temperatures (5–20 °C) is severely limited by the slow hydrolysis of entrapped solids that accumulate in the sludge bed when high loading rates are applied (Zeeman and Lettinga, 1999). The solids accumulation will impose a more frequent sludge discharge. Consequently, the excess sludge will increase leading to a low solids retention time (SRT) and a concomitantly less stabilised sludge bed with a low specific methanogenic activity (SMA). The latter will result in a poor soluble COD removal and an overall deterioration of the digestion process. The performance of the one-stage UASB reactor in Palestine when operated at short HRT similar to those in tropical countries will most likely be limited by the high imposed organic and solids loading rates. Leitão et al. (2006) pointed out that the use of UASB reactors for treatment of sewage with relatively high COD concentration is still undergoing trials and argued that such knowledge is important to improve the reliability of anaerobic processes.

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The anaerobic sewage treatment is certainly not limited to tropical countries neither to sewage of rather low strength (Mahmoud, 2002). The results of anaerobic sewage treatment in a 64 m^3 one-stage UASB reactor operated in Jordan revealed that it is quite possible to operate the reactor under the conditions of Jordan and Palestine. In this case the reactor should be operated at a prolonged hydraulic retention time of more than 22 h (Mahmoud et al., 2004b; Halalsheh et al., 2005). The reactor in Jordan was monitored after one and a half year of operation and no data had been published on the start up phase and the reactor performance during the first year of operation. As an alternative approach to the one-stage UASB reactor, Mahmoud et al. (2004b) investigated a novel pilot-scale system consisting of an integrated high loaded UASB reactor and digester, namely UASB-digester system. In the proposed system a parallel digester unit is incorporated for enhanced sludge stabilisation and generation of active methanogenic sludge to be recirculated to the UASB reactor. The obtained results were promising as compared with the one-stage UASB reactor. Nonetheless, the system was only investigated in the Netherlands but had never been investigated in the Middle-East region, where climate and sewage characteristics are quite different.

In the present work, the anaerobic sewage treatment using a one-stage UASB reactor and a UASB-digester system in Palestine was investigated. A pilot-scale high loaded one-stage UASB reactor was started up without inoculation and operated for a period of more than a year at an HRT of 10 h. The one-stage UASB reactor was operated in order to elucidate the influence of seasonal temperature fluctuations on the system performance over the first year of operation. This is of particular importance to have base line records to be used as reference values to asses the achievements obtained from incorporating a digester. Afterwards, the one-stage UASB reactor was modified to a UASB-digester system by incorporating a digester operated at 35 °C in order to asses the system performance.

2. Methods

2.1. Experimental set-up

The experimental work was carried out over two successive periods at Al-Bireh wastewater treatment plant in Palestine. Firstly, a pilot one-stage flocculent sludge UASB reactor (volume, height, diameter: 140 l, 325 cm, 23.5 cm) was operated at ambient air temperature. Afterwards, the one-stage UASB reactor was modified to the UASB-digester system by incorporating a CSTR digester (working volume 106 l). A schematic diagram of the experimental set-up is illustrated in Fig. 1. The UASB reactor and the digester were constructed from Plexiglas and PVC tubes, respectively. The temperature of the digester content was controlled by recirculating thermostated water of 35 °C through a tube placed around the reactor. Taps were installed over the whole UASB reactor height at about 25 cm apart for sludge discharge, re-circulation and analysis. The digester content was continuously mixed at around 60 rpm.

2.2. Operation and start up of pilot reactors

2.2.1. One-stage UASB reactor

The one-stage UASB reactor was started up during spring specifically in April, coinciding the beginning of the hot period in Palestine. It was operated for a period of more than a year at ambient temperature and 10 h HRT. The reactor was fed with domestic sewage pre-treated with screens and grit removal chamber. The sewage was pumped every 5 minutes to a holding tank (200 l plastic container), with a resident time of about 5 minutes, where the reactor was fed and the influent was sampled (Fig. 1). Daily monitoring was started since the onset of the experiment including ambient air temperature and biogas production, as well as grab influent and effluent wastewater samples analysis for total COD. The influent and effluent were analysed for COD_{tot} and the distinguished COD fractions over the hot and cold periods of the year. After 144 days of operating the one-stage UASB reactor, five influent and effluent samples were collected and analysed during a period of 35 days for BOD, TSS, NH_4^+ and PO_4^{3-}. The atmospheric pressure was measured in situ. The one-stage UASB reactor was operated for 389 days of which the first 42 days were considered as a "start-up" period.

2.3. UASB-digester system

The digester was inoculated with activated sludge collected from the thickener of the extended aeration wastewater treatment plant of Al-Bireh City, Palestine. During the operation of the one-stage UASB reactor, the digester was continuously fed with activated sludge after being diluted to around 20 gTS/L with VS/TS ratio of 0.74 so as to achieve a SRT of 20 days. The digester was operated in this mode for a period of four months to accelerate the digester start up. Afterwards the digester was incorporated to the one-stage UASB reactor. The sludge bed of the UASB reactor of the UASB-digester system was kept below 40 cm from the bottom of the reactor, by discharging the sludge accumulated above 2–3 times a week. The discharged sludge was collected in a bucket, from where the sludge was immediately fed to the digester by a peristaltic pump. At the same time, the digester effluent was pumped out to another bucket, while a third pump was recirculating it to the lower part of the UASB reactor at 10 cm from the bottom. Sludge was never wasted during the system operation. The UASB-digester system was operated for 107 days of which the first 57 days were considered as a "start-up" period. The influent and effluent of the UASB-digester system was monitored for biogas production, temperature and COD measurements. A set of six samples was analysed during the steady state period for COD_{tot} and COD fractions, TSS, NH_4^+ and PO_4^{3-}.

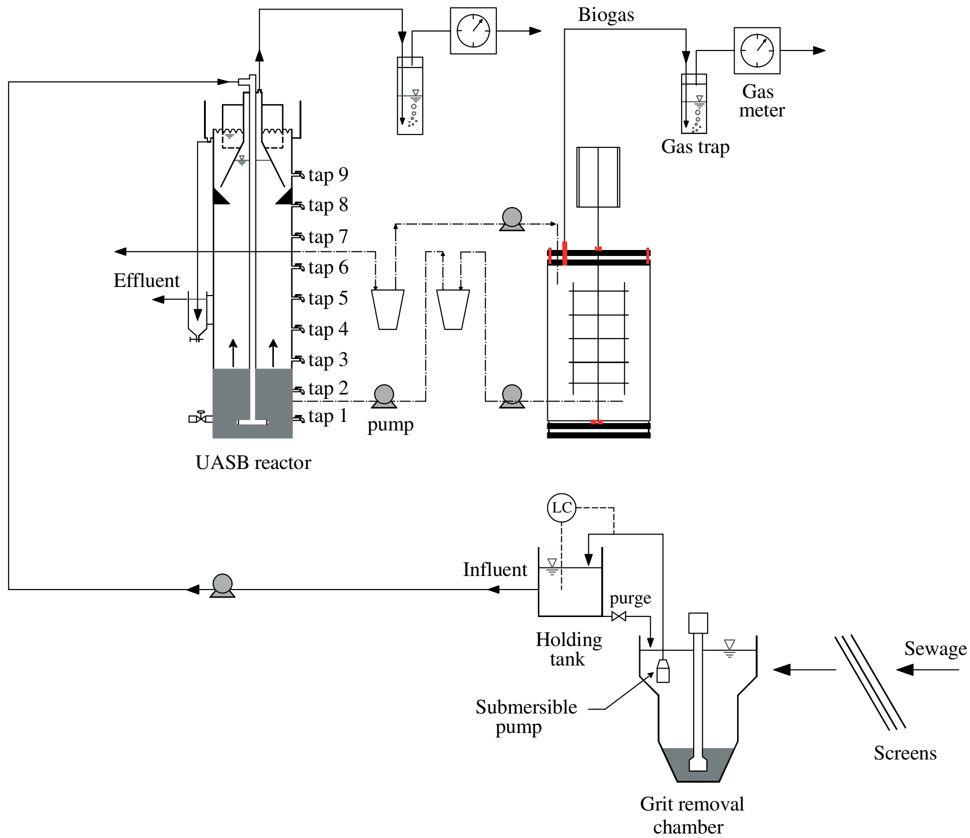

Fig. 1. Schematic diagram of the UASB-digester system pilot plant; LC = level controller.

2.4. Analytical methods

Total suspended solids (TSS), volatile suspended solids (VSS), total solids (TS), volatile solids (VS), ammonium (NH_4^+), chemical oxygen demand (COD), biological oxygen demand (BOD), $PO_4^{3-}-P$, and SO_4^{2-} were measured according to standard methods (APHA, 1995). Raw samples were used for measuring total COD (COD_{tot}), 4.4 μm folded paper filtered (Schleicher and Schuell 5951/2, Germany) samples for paper filtered COD (COD_p) and 0.45 μm membrane – filtered (Schleicher and Schuell ME 25, Germany) samples for dissolved COD (COD_{dis}). The suspended COD (COD_{ss}) and colloidal COD (COD_{col}) were calculated as the difference between COD_{tot} and COD_p and the difference between COD_p and COD_{dis}, respectively. The volatile fatty acids (VFA) analysis was carried out as described by Buchauer (1998). All samples were analysed in duplicate. Methane evolved from the reactors was determined by the gas displacement method using 5% NaOH solution.

2.5. Calculations

2.5.1. COD balance

$$COD_{tot,inf} = COD_{accumulated} + COD_{CH4\ UASB} + COD_{CH4\ digester} + COD_{tot,eff}$$

where

$COD_{tot,inf}$ and $COD_{tot,eff}$: amount of total COD in influent and effluent (mgCOD/l)

COD_{CH4} : amount of produced CH_4 (liquid form+gas form)

$COD_{accumulated}$: amount of accumulated or not detected COD (mg/l)

3. Results and discussion

3.1. Sewage characteristics

The characteristic of raw sewage used in this research is depicted in Table 1. The sewage is characterized with high concentration of pollutants according to the sewage strength classification proposed by Metcalf and Eddy (2003) and Henze (1997). The high sewage strength is also clear when compared with sewage characteristics in several countries in Europe, Asia and Latin America (Mahmoud et al., 2003a). The high sewage strength in Palestine is postulated to low water consumption and people's habits (Mahmoud et al., 2003a). The influent COD was mainly in the suspended form followed by dissolved then colloidal of, respectively 62%, 25% and 13%. Around 36% of the influent dissolved COD was in the VFA form.

Table 1
Influent and effluent COD_{tot} and fractions and removal efficiencies (%) during anaerobic sewage treatment in a one-stage UASB reactor operated during the cold and warm parts of the year and a UASB-digester system

	Parameter	UASB reactor						UASB-digester		
		Hot period			Cold period					
		April 05–Oct. 05			Oct. 05–April 06			July–Aug. 06		
		From day 42 to 196			From day 196–377			From day 446–496		
		#	Average	Range	#	Average	Range	#	Average	Range
Influent	COD_{tot}	24	1394(132)	1159–1701	28	1137(188)	770–1525	6	1186(272)	844–1534
	COD_{ss}	22	826(167)	548–1176	4	1024(160)	875–1244	6	767(177)	592–1089
	COD_{col}	22	196(61)	110–380	4	128(135)	35–321	6	111(83)	44–268
	COD_{dis}	22	376(69)	226–471	4	182(20)	162–209	6	308(90)	181–395
	VFA	19	123(42)	34–193				6	110(27)	79–157
Effluent	COD_{tot}	20	620(95)	443–782	26	780(144)	569–1091	6	318(24)	285–345
	COD_{ss}	20	215(69)	110–380				6	191(21)	163–221
	COD_{col}	20	120(56)	17–220				6	22(13)	6.75–42
	COD_{dis}	20	285(87)	133–518				6	105(19)	77–128
	VFA	18	113(49)	22–196				6	33(20)	0–57
Removal (%)	COD_{tot}	20	55(7)	43–69	26	32(13.5)	5–57	6	72(5.5)	63–78
	COD_{ss}	18	73(10)	57–89				6	74(5.2)	66–80
	COD_{col}	18	40(26)	−8–89				6	74(19)	40–95
	COD_{dis}	18	21(21)	−22–59				6	62(18)	30–78
	VFA	17	−4.5(57)	−170–71				6	70(19)	48–100

Standard deviations are shown in parenthesis.

3.2. Organic loading rate

The one-stage UASB reactor was operated at high organic loading rates (OLR) of 3.35(0.32) and 2.73(0.45) g COD/l d during the hot six months of the year and the other cold six months, respectively. Similarly, the UASB reactor in the UASB-digester system was operated at a rather high OLR of 2.84(0.66) g COD/l d.

3.3. COD removal efficiency

During the start up period, the one-stage UASB reactor performed as an enhanced settler as COD removal started directly since the onset of the reactor operation. The achieved removal efficiencies during this period of operation (average of 5 measurements over the first 42 days of operation) for COD_{tot}, COD_{ss}, COD_{col} and COD_{dis} were 48, 64, 12 and 28%, respectively.

The results presented in Fig. 2 and Table 1 reveal high temperature dependence of the process performance. During stage 1, the UASB reactor was operated as a high loaded one-stage UASB reactor. Although the reactor was started without inoculation, the COD effluent quality was almost stable, with a sort of rather improving trend, during the first six months of operation (0–160 days). This operation period coincided the hot period of the year (April–September). Right after, and during the period October–March (160–330 days), the temperature dropped down accompanied with clear deterioration in effluent quality and removal efficiency. Afterwards and up to April (during the period 330–390 days) the temperature was increasing but the effluent quality was not proportionally improved. After more than a year of continuous operation of the one-stage UASB reactor, sludge from the digester was started to be recirculated from the digester starting at the beginning of stage 2. During this period, a sharp decline in effluent COD concentration was achieved and this period was considered as a start up period of the UASB-digester system. Stage 3 which lasted for around two months of operation and monitoring with continual sludge re-circulation was considered as a steady state period. During this stage, the COD_{tot} effluent concentration was exceptionally low of 318 (24) mgCOD/L, and the achieved COD_{tot} and TSS removal efficiencies were rather high of, respectively 72(5.6)% and 93(6)%. The effluent quality during this period (stage 3) was quite stable as clear from Fig. 2 and the low standard deviations of the COD concentration and COD removal efficiency of, respectively 24 and 5.6.

3.4. Nutrients removal

The achieved NH_4^+ and PO_4 removal efficiencies in both reactors were very low (Table 2). The results clearly demonstrate that UASB reactors are not sufficient for removing nutrient from wastewater. In the UASB reactors only a change in the chemical forms of nitrogen and phosphorous take place as reported by Bogte et al. (1993). Therefore, a nutrient removal, when necessary, can be achieved in a separate post-treatment step (Haandel and Lettinga, 1994).

3.5. Sludge bed development

The course of sludge bed development during the whole period of operation is depicted in Fig. 3. The results reveal

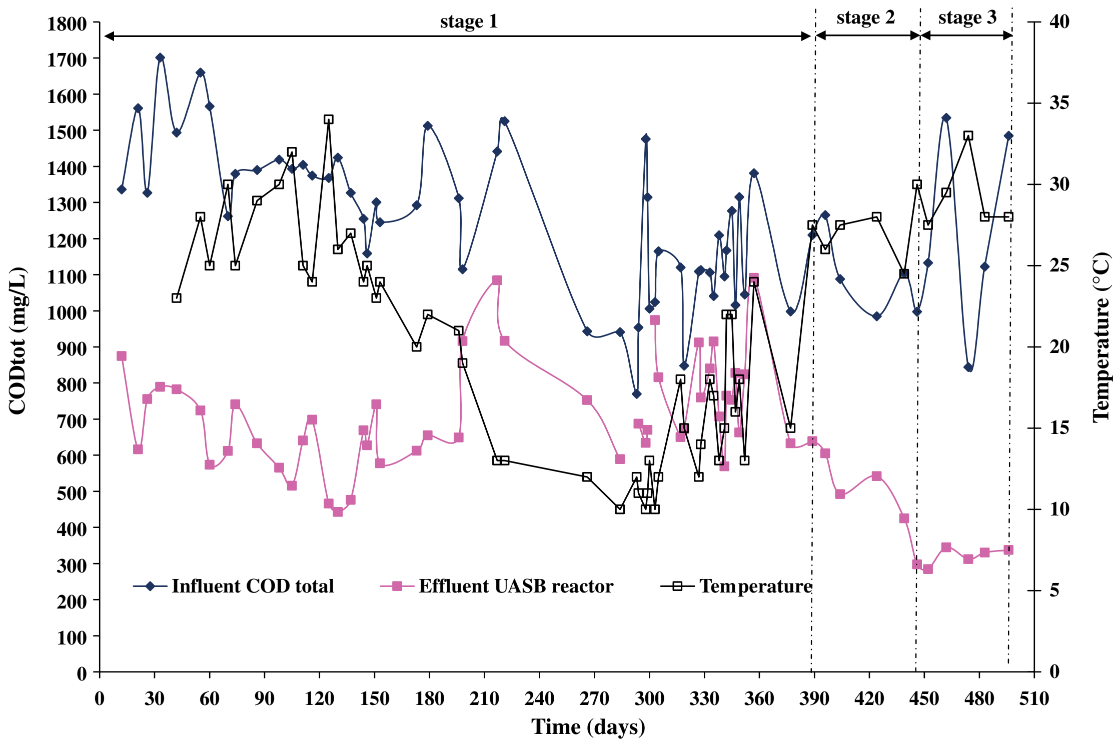

Fig. 2. Influent and effluent COD_{tot} concentration and ambient air temperature during the anaerobic treatment of domestic sewage from Al Bireh City/Palestine in a one-stage UASB reactor (stage 1) and a UASB-digester system (stages 2 and 3). Stages 2 and 3 stand for start up and steady state periods of the UASB-digester system.

Table 2
Influent and effluent characteristics in terms of COD_{tot}, BOD, TSS, PO_4 and NH_4^+ during anaerobic sewage treatment in a one-stage UASB reactor and a UASB-digester system

Parameter	Unit	One-stage UASB reactor			UASB-digester system		
		From day 144–day 179[a]			From day 57–day 107[b]		
		$N = 5$			$N = 6$		
		Influent	Effluent	Removal	Influent	Effluent	Removal
COD_{tot}	mg/l	1250(56)	645(63)	48(4.56)	1186(272)	318(24)	72(6)
BOD_5	mg/l	588(72)	308(68)	47(13)			
TSS	mg/l	1571(159)	1135(135)	27.8(3)	1125(631)	69(49)	93(6)
NH_4-N	mg/l	63(16)	48.8(15)	22.1(10)	84(5)	88(6)	−5(10)
PO_4-P	mg/l	12.63(5)	12.3(4)	−2.5(10)	14(1)	13(2)	8(11)
T air	°C	23(1.8)			29(2)		

Standard deviations are shown in parenthesis.
[a] The zero day is the first day of operating the UASB reactor in April 2005.
[b] The zero day is the first day sludge from the digester fed to the UASB reactor in June 2006.

clearly the successful sludge bed development in the one-stage UASB reactor without inoculation during two months of operation. Solids were accumulated gradually with temperature decline. The reason of that is limited hydrolysis of the entrapped solids which is in agreement with the results presented by de Man (1990). The sludge accumulation was accompanied with effluent quality deterioration (Fig. 2). The high TSS concentration in the effluent of the one-stage UASB reactor (Table 2) reveal that sludge was mainly removed by being washed out in the effluent. This is attributed to the poor conversion of the accumulated solids which would result in spill out of digestion intermediate products with the effluent. In addition, Mahmoud et al. (2003b) reported that when biogas production is low, the provided mixing is insufficient. Consequently channeling of wastewater through the sludge bed might occur, thus decreasing removal efficiency. Moreover, the hydraulic mixing in the reactor was rather low. The upflow velocity in the reactor was 0.3 m/h which is less than the recommended values of 0.5–1.0 m/h. Afterwards, when temperature started to increase sludge started to be degraded, and sludge profile became rather stable particularly when the one-stage UASB reactor was modified to a UASB-digester system.

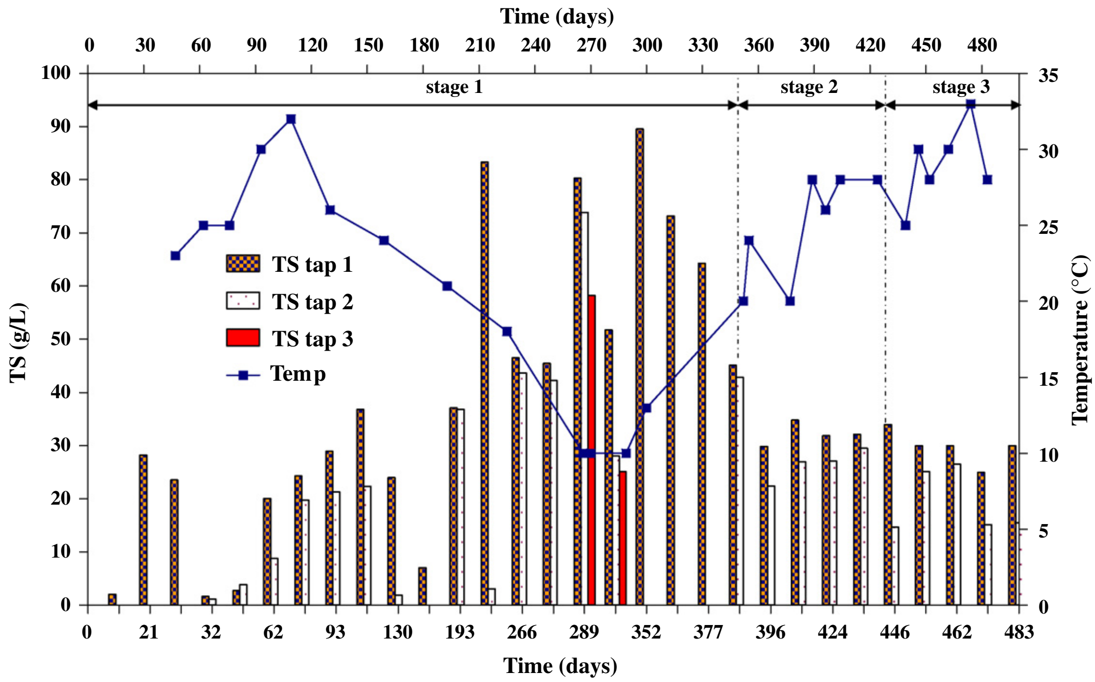

Fig. 3. Course of sludge bed development in terms of TS concentration in a one-stage UASB reactor (stage 1) and a UASB reactor of a UASB digester system (stages 2 and 3) and ambient air temperature.

The pattern and profile of the VS/TS ratio presented in Fig. 4 is not showing any dependency on the sludge bed height. Therefore, sludge from the bottom of the reactor with the highest concentration is preferable to be recirculated to the digester, in order to reduce the latter volume. Mahmoud et al. (2004b) reported similar findings. The VS/TS ratio of the sludge in the sludge bed of the one-stage UASB reactor was the highest during winter period indicating the poor conversion of accumulated solids. Afterwards, the VS/TS ratio had decreased to a mean value of 59% when the one-stage UASB reactor was modified and operated as a UASB-digester system (Table 3). The incorporation of the sludge digestion bed resulted in remarkable stabilization of the accumulated solids. This is clear from the disappearance of solids at tap 3 and the low VS/TS ratio at tap 1 and 2. Worth mentioning that sludge was never wasted, yet partly and occasionally accumulated, from the both operated systems. The extremely low sludge production is a remarkable feature of the anaerobic processes.

According to Cavalcanti et al. (1999), to avoid the discharge of sludge in the effluent, it is necessary that excess sludge be discharged periodically from the reactor before its storage capacity is exhausted. However, in the present case, the storage capacity of the reactor was not exhausted, neither the effluent SS could be reduced. Rather, the UASB reactors are usually operated with sludge bed volume of about 50% of the total reactor volume with minimum height of sludge bed not less than 1.0 m to avoid short circuiting of the influent. The sludge bed height of the investigated UASB reactor was maximum 0.85 m for few days and for remaining days it was less or equal to 0.50 m. Since very small sludge bed height has been adopted, it has resulted in less COD removal efficiency. High SS concentration in the effluent might also be addressed to non-proper functioning of gas–liquid–solids (GLS) separation device. For instance, the tentative deign criteria for the design of the gas–solids separator requires that the height of the gas collector to be between 1.5 and 2 m at reactors height 5–7 m. The surface area of the apertures between the gas collector and the reactor walls was 20% of the reactor surface. This resulted in an upflow velocity in the apertures inlet of 1.6 m/h which satisfies the GLS design guidelines (Vieira and Souza, 1986; Lettinga and Hulshoff Pol, 1991).

3.6. COD mass balance over the UASB-digester system

The mass balance over the UASB-digester system revealed that the main conversion took place in the UASB reactor. In the digester only 1% of the influent COD_{tot} was converted to methane gas. This is in agreement with the results previously presented by Mahmoud et al. (2004b). During the whole period of operation of around four months, no sludge was discharged as sludge accumulation was minimal. This strongly indicates the high conversion of the removed COD in the UASB reactor. The effluent dissolved COD and VFA were very low indicating good methnogenic conditions (Table 1). In addition to enhancing the sludge quality in the UASB reactor, it is likely that the incorporated digester had improved the mixing in the UASB reactor because of sludge recirculation and hence

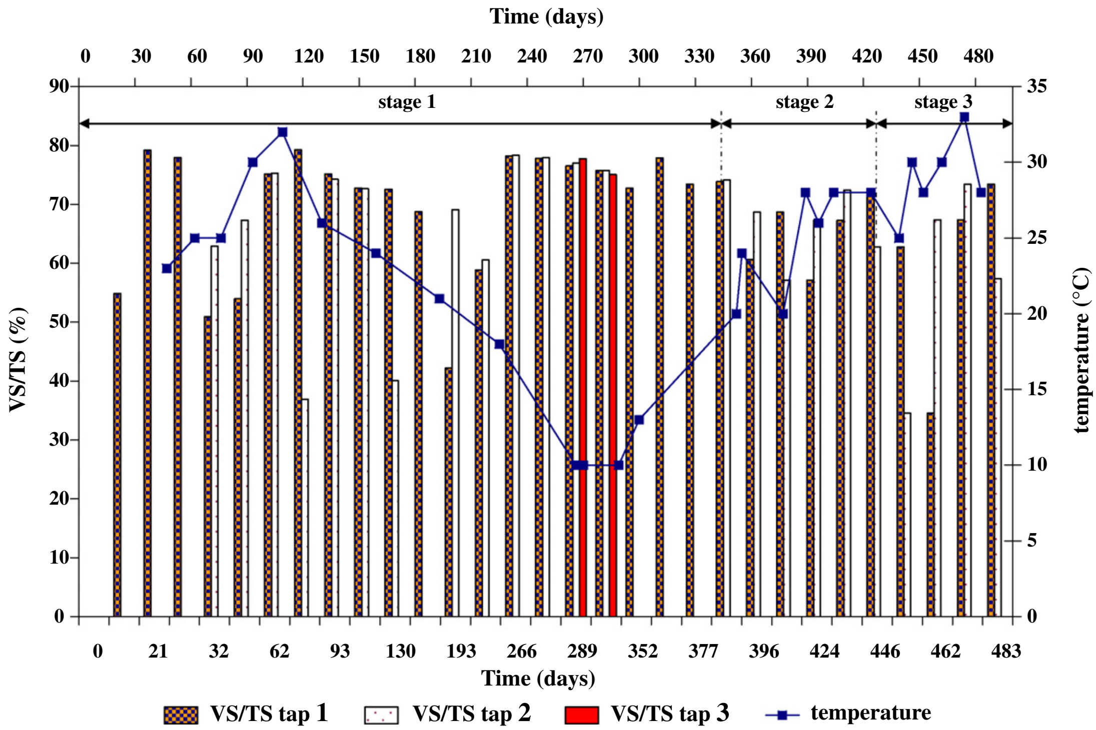

Fig. 4. VS/TS ratio over sludge bed height of a one-stage UASB reactor (stage 1) and a UASB reactor of a UASB-digester system (stages 2 and 3) and ambient air temperature.

Table 3
VS/TS profile along the sludge bed height of a one-stage UASB reactor operated during the cold and warm parts of the year and a UASB reactor of a UASB-digester system

Location	UASB reactor				UASB-digester	
	Hot period		Cold period			
	April 05–Oct. 05		Oct. 05–April 06		July–Aug. 06	
	From day 12–196		From day 196–377		From day 446–496	
	#	Average	#	Average	#	Average
Tap 1	12	67(13)	8	74(6)	5	62(16)
Tap 2	8	62(15)	4	73(8)	5	59(15)
Tap 3		No sludge	2	76(0.5)		No sludge

Standard deviations are shown in parenthesis.

improved performance of the reactor. The low sludge production had resulted in long SRT operation of the digester reaching values as high as 100 days. However, the sludge volume in the UASB reactor is expected to increase with time, thus improving the system physical and biological performance. Halalsheh et al. (2005) reported sludge bed development for more than 1 m high after around three years of starting a UASB reactor treating concentrated sewage in Jordan. Under such conditions, more digestion will take place in the digester.

3.7. Final discussion

The COD removal efficiency of 72% attained in the UASB reactor of the UASB-digester system is higher than those achieved in well functioning UASB reactors operated in sub-tropical regions at much lower loading rates. Halalsheh et al. (2005) reported COD_{tot} removal efficiency of 58% while treating concentrated sewage in a one-stage UASB reactor in Jordan. The latter UASB reactor was operated during summer time at 23–27 h HRT (OLR 1.4–1.6 $kgCOD/m^3$ d). The achieved COD removal efficiencies in the UASB-digester system are even as high as those reported in tropical countries with almost similar HRT of 10 h. In tropical countries the achieved COD removal efficiencies are in the range of 51–74% (Von Sperling and Chernicharo, 2005; Aiyuk et al., 2006).

The UASB-digester system was operated during summer time, so the enhancement in the UASB reactor performance can not be merely attributed to the modified setup of the UASB-digester system. However, the achieved COD removal efficiency in the UASB-digester system was higher than those achieved in the one-stage UASB reactor over the whole first year. The system even performed better than previously researched UASB reactors that had been operated at much higher HRTs of 2 and 4 days at the same wastewater treatment plant of Al-Bierh City where this research was conducted (Al-Shayah and Mahmoud, 2008).

The performance of the UASB-digester system was mainly evaluated under higher temperature conditions. Hence it will not be appropriate to conclude that this performs better than UASB reactor alone. The performance of UASB-digester system should be compared at lower temperature and then the conclusion can be drawn. However, better performance of the UASB-digester system is evident from the results presented for hot temperatures. Though, it becomes more and more evident that the problem of solids accumulation during the cold period of the year can be handled successfully by incorporating a sludge digester.

The digester volume can also be substantially reduced, as Mahmoud et al. (2004a) showed hardly any improvement in the digester performance at increasing the SRT above 10 days at 35 °C. Moreover, due to solids content stratification in the sludge bed of the UASB reactor while maintaining a uniform stability, sludge with high concentration can be conveyed from the UASB reactor to the digester which is in agreement with the results previously presented by Mahmoud et al. (2004a).

4. Conclusions

- The performance of the investigated one-stage UASB reactor was limited by the low temperature during winter time and the high strength and solids content. The one-stage UASB reactor achieved removal efficiencies for total, suspended, colloidal, dissolved and VFA COD of 54, 71, 34, 23%, and −7%, respectively during the first warm six months of the year, and achieved only 32% removal efficiency for COD_{tot} over the following cold six months of the year.
- The UASB-digester system represents an efficient technology for anaerobic (pre)treatment of high strength sewage during summer time, i.e. it provides average removal efficiencies for COD_{tot}, COD_{ss}, COD_{col} and COD_{dis} of 72%, 74%, 74% and 62%, respectively.
- The performance of the UASB-digester system should be assessed and demonstrated in Palestine during winter time.

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